A Framework for Predicting the Residual Load Carrying Capacity of Concrete Structures Exposed to Aggressive Environments

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Abstract

Reinforced concrete structures are susceptible to a variety of deterioration mechanisms due to creep and shrinkage, alkali-silica reaction (ASR), carbonation, and corrosion of the reinforcement. The deterioration problems can affect the integrity and load carrying capacity of the structure. Substantial research has been dedicated to these various mechanisms aiming to identify the causes, reactions, accelerants, retardants and consequences. This has improved our understanding of the long-term behaviour of reinforced concrete structures. However, the strengthening of reinforced concrete structures for durability has to date been mainly undertaken after expert assessment of field data followed by the development of a scheme to both terminate continuing degradation, by separating the structure from the environment, and strengthening the structure. The process does not include any significant consideration of the residual load-bearing capacity of the structure and the highly variable nature of estimates of such remaining capacity. Development of performance curves for deteriorating bridge structures has not been attempted due to the difficulty in developing a model when the input parameters have an extremely large variability.

This paper presents a framework developed for an asset management system which assesses residual capacity and identifies the most appropriate rehabilitation method for a given reinforced concrete structure exposed to aggressive environments. In developing the framework, several industry consultation sessions have been conducted to identify input data required, research methodology and output knowledge base. Capturing expert opinion in a useable knowledge base requires development of a rule based formulation, which can subsequently be used to model the reliability of the performance curve of a reinforced concrete structure exposed to a given environment.

Keywords: Reinforced concrete, aggressive environment, degradation, and residual capacity

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1.0 Introduction

Reinforced concrete has been one of the most used building materials in the last decades. It has proven to be a reliable material with a good durability performance compared to steel and other structural materials. However, early deterioration of concrete due to aggressive environments or poor construction quality has occurred in many reinforced concrete structures. Selection of a remedial action for aging/deteriorating infrastructure and designing new projects with sustainability objectives is a challenge faced by asset managers and designers of civil infrastructure. The fast rate of deterioration and the high cost of repair, rehabilitation and replacement of concrete structures have become major issues in infrastructure asset management. Even when the resources have been allocated, completing rehabilitation tasks with minimal interruptions and inconvenience to the public has been a dominant factor in identifying a given method of rehabilitation.

Deficient reinforced concrete structures may be subdivided into two basic types – structurally deficient and functionally obsolete. Structurally deficient structures are those with deteriorated structural components, which require restrictions to be placed on their usage by the public as a result of inadequate load carrying capacity. Functionally obsolete structures are the those that cannot meet the new strategic function and level of use. These structures may have older design features that prevent them from accommodating current design loads/criteria.

Decisions for rehabilitation based on initial cost can inhibit innovation since, generally; innovative solutions have a high initial cost. A probabilistic whole of life cycle costing analysis can be used to obtain a more realistic assessment of the benefits of innovative materials and technologies, while giving the asset manager a basis to arrive at an acceptable level of risk, taking into account the reliability of proven/traditional solutions weighed against that of innovative solutions.

A new research project initiated at RMIT University, funded by corporative research centre for construction innovation (CRC-CI) in Australia, is aimed to develop a decision support tool for identification of cause and selection of remedial action for reinforced concrete structures susceptible to degradation through exposure to aggressive environments such as marine conditions, extreme arid conditions and chemically active soils. The decision support tool will account for uncertainties associated with the innovative technologies using a probabilistic concept, permitting the engineer to quantify and accept the level of reliability associated with the design. The research outcome can also be used for the design of more sustainable civil infrastructure in aggressive environments

2.0 Decision Support Framework

Many organizations face the need to evaluate multiple program proposals or projects competing for scarce resources. Most of the time, the decision maker is attempting to satisfy conflicting objectives or cater for opposing group interests. The challenges faced in developing an integrated decision making framework are both procedural and conceptual. In operational terms, the framework should be easily understood and employed. In philosophical terms, the framework should be able to deal with challenging issues, such as uncertainty, time frame, network effects, model changes, while integrating cost and non-cost values into the evaluation. The choice of evaluation technique depends on the features of the problem at hand, on the aims of the analysis, and on the underlying information base [1]. A decision support framework was developed after identifying the most important factors (Figure 1).

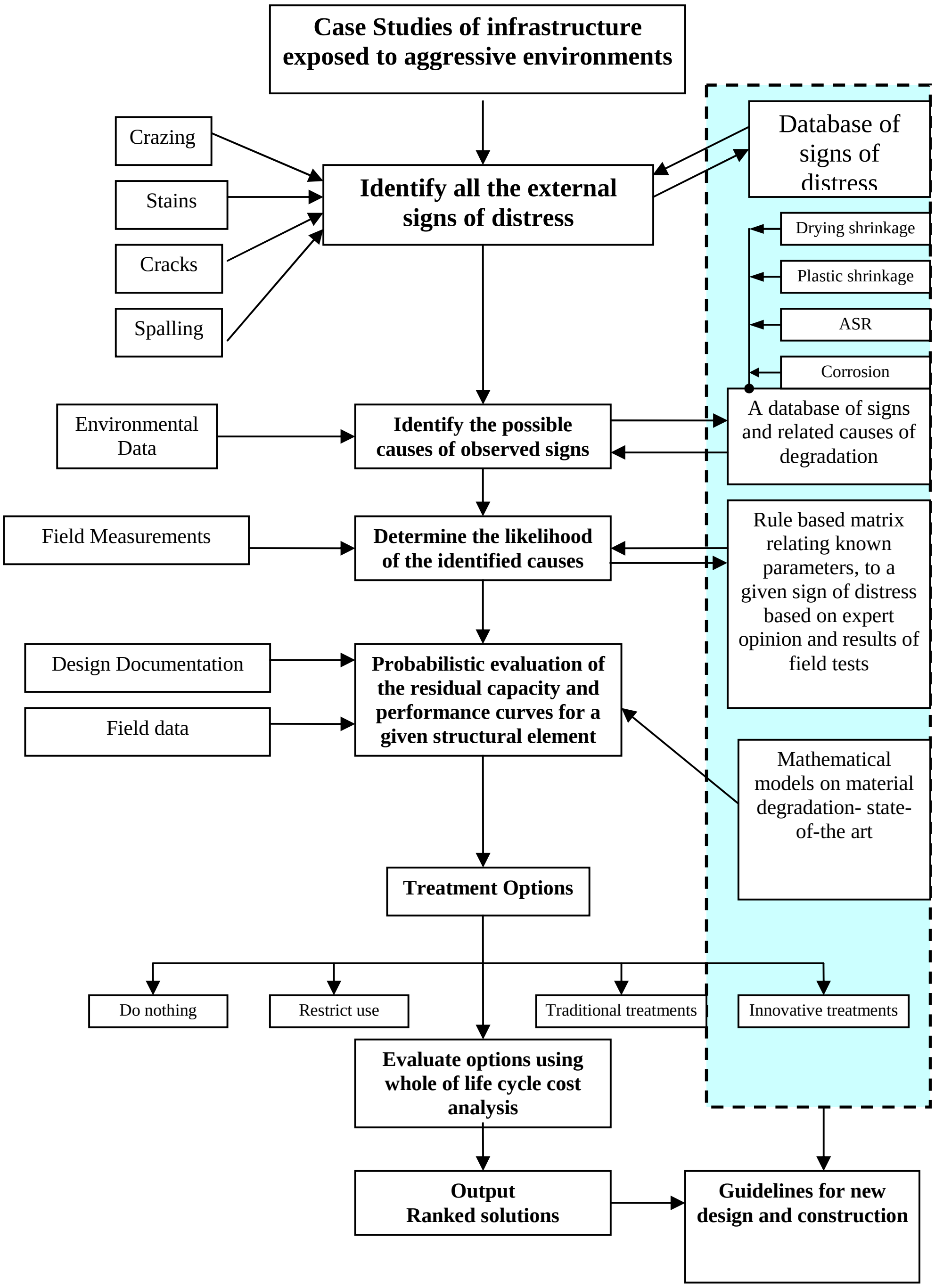

Figure 1: Proposed decision support framework

The framework was developed around three key tasks: Case studies of deteriorating reinforced concrete structures exposed to aggressive environments, evaluation of the residual capacity using a probabilistic methodology and then conducting a life cycle cost analysis for each of the options.

3.0 Case Studies of Deteriorated Structures Exposed to Aggressive Environments

Case studies are analysed to identify external signs of distress and the additional investigation results that usually follow initial observations. Crack patterns and locations, stains, spalling of concrete, excessive deflections, discolouration can be caused by a number of mechanisms. The occurrence of any single mechanism is complex and dependent on a number of variables. Such variables include concrete type, quality and mixture, environmental conditions, soil type, ground-water chemistry and level, type of structure, design, and seasonal variation (e.g. water/humidity level, rainfall and temperature). Therefore, site description, classification of external signs of distress, sampling, testing and monitoring procedures need to be established to determine which variables and signs of distress are most likely to be relevant to a specific deterioration mechanism. Methods of identifying, monitoring and predicting causes of degradation are also evaluated. In view of the large amount of data, an extensive database system is to be developed and used along with environmental data to identify the possible causes of observed sign of distress. A rule based matrix founded on expert opinion and results of field tests was adopted as the means of relating known parameters to given signs of distress. Using this approach the likelihood of the identified cause(s) may also be determined.

3.1 Site selection

It is reported by Fenwick & Rotolone [2] that in Australia, Queensland Department of Main Roads (QDMR) manages a state controlled road network of some 33,000 km, which contains some 2850 bridges. This primary network carries over 80% of the freight traffic. Table 1 shows the major construction materials used in the existing network of bridges in three time periods.

Table 1 Age and Material Distributions of Bridges [2]

Bridge Material	**Oldest still in service**	**Number of Bridge Built**			**Subtotal**
		Pre 1950	**1950-1976**	**Post 1976**	
Timber	1886	322	177	1	500
Reinforced Concrete	1896	49	60	17	126
Steel	1886	32	187	12	231
Pre-Stressed Concrete	1954	0	679	1319	1998
Total		403	1103	1349	2855

QDMR has a significant investment in concrete infrastructure in relation to Queensland's transport needs. The financial value of this investment is approximately A$3 billion with the majority invested in concrete bridges followed by drainage structures and concrete roads [3]. Since 1985, concrete bridge structures throughout Queensland have been regularly examined and reported for the presence of any deterioration mechanisms. Approximately 105 bridges have now been identified as suffering from significant deterioration. Of these bridges, around 10 are classified as severe cases [3]. The first stage of the selection process consists of a risk assessment. A 'structure risk' is identified for those structures that have a structural form or contain particular details that would make the consequences of concrete deterioration more critical. A review is subsequently undertaken of the principal inspection and the more recent general inspection reports. The study also investigates the deteriorated structures where bridge rehabilitation works are underway or have already been completed.

3.2 Sampling and testing

The principal objective of the data collection is to identify signs of distress and to establish the spatial distribution of attack to the concrete in terms of area, approximate crack widths, spalling, stains and crazing. Secondary features are to be examined including the profile of the concrete surface in conjunction with the depth of softening and laboratory data to confirm vulnerability of the steel reinforcement. The samples of concrete comprise 50-100 mm diameter cores, drilled dust or chiselled fragments and lump samples. The in-situ testing involved hammer soundness surveys, rebound hammer tests, string-line measurements and localised breaking out of the concrete. To ensure a degree of uniformity in approach between different sites and individuals a set of project specific procedures are established in line with QDMR inspection and maintenance programs. The precise methodology adopted varies due to local constraints (eg access) and particular diagnosed deterioration mechanisms. For efficiency, soil sampling is combined with concrete sampling wherever possible. For many deterioration mechanisms the occurrence of wet conditions and the chemical content in the ground surrounding the concrete is a significant factor. Therefore, groundwater sampling and monitoring is considered essential to the investigation.

The soil samples are subjected to physical, chemical and mineralogical tests and the groundwater samples are subjected to chemical testing. The general objective of the laboratory testing is to classify the sites and to highlight simple physical tests to routinely screen existing structures and potentially aggressive sites.

The tests undertaken on concrete may be grouped as follows: physical testing, chemical testing, and petrographic examination. The tests have the following overall objectives:

- To characterise the concrete within different members at each site for comparison against the severity of attack to assess trends;
- To determine the extent and nature of the deterioration to assist in formulating repair strategies;
- To establish a database of fundamental information on the concrete so that the processes and factors associated with different deteriorating mechanism and durability of the structure can be better understood.

The potential composition of the cement is estimated in terms of tricalcium aluminate, tricalcium silicate, dicalcium silicate and tetracalcium aluminoferrite content.

3.3 Environmental data

Increasing temperature and humidity results in an increase of cracking and deterioration. Hence, climatic averages of temperature and rainfall give an indication of aggressive and non-aggressive zones. Table 2 gives an indication of the range of climate conditions within Queensland. Rainfall and associated humidity are seen to vary, from location to location, more significantly than prevailing temperature.

Table 2: Range of climatic condition [4]

Location	Mean 3 pm Temperature (^oC)	Mean 3 pm Humidity (%RH)	Annual Mean Rainfall (mm)
Cloncurry	31.5	25	472
Warwick	23	44	716
Maryborough	25.2	56	1187
Townsville	27.3	57	1195
Cairns	27.5	60	2036

4.0 Evaluation of the Residual Capacity

Reinforced concrete structures are susceptible to a variety of deterioration mechanisms including alkali-silica reaction (ASR), carbonation, chloride ingress, and corrosion of the reinforcement. The deterioration problems can affect the integrity and load carrying capacity of the structure. Substantial research has been dedicated to identify the causes, reactions, accelerants, retardants and consequences. This has improved our understanding of the long-term behaviour of the reinforced concrete structures and has enabled mechanical models to be developed that predict the residual strength of the structure. The resistance to deterioration of reinforced concrete structures can also be enhanced by using these models [5].

In order to develop an understanding of the residual life and the optimum time for intervention in the process of deterioration, an establishment of the performance curve for a deteriorating structural element is essential. This requires structural analysis using modified material strengths and rates of reduction of material strengths established using mathematical models on material degradation. These combined with the probabilistic methods to develop an innovative methodology for assessment of the residual life of deteriorating structures and hence develop future performance curves [6].

5.0 Treatment options

This is an important component of the framework. Options available to the authorities have been expanded with new developments in materials and technology. However, a lack of availability of complete information hinders an objective and fair comparison, making it difficult for the asset manager to arrive at an informed decision. The broad range of higher-level management options (identified by QDMR) is given below.

- Do nothing
- Restrict use
- Maintain and monitor
- Traditional treatments

- Innovative treatment
- Replace super-structure
- Replace entire bridge

Recent developments related to materials, methods and techniques for structural strengthening and rehabilitation of deteriorated bridges have been significant. In addition to well-established and proven technologies such as steel plate bonding, external post tensioning, concrete encasing, etc., innovative technologies such as use of fibre reinforced polymer composites are appearing in the market place. Evaluation of different options requires the asset manager to find a basis for comparison of the options. An evaluation process needs to include an allowance for the greater level of uncertainty associated with the innovative methods as opposed to the current methods.

6.0 Evaluation of the Treatment Options

Presenting clear and concise information to the decision maker regarding the available options will enable him/her to make a higher-level decision from the list identified above. Detailed discussions with industry revealed that the “cost” is the prime deciding factor in making a decision in selecting a particular strengthening scheme. Authorities prefer to be presented with the whole of life cost of a selected treatment option and incorporate other factors through their own judgment using a broader framework covering social and environmental issues [7]

7.0 Whole of Life Cycle Analysis

The Whole of Life cycle cost analysis (WLCCA) is an evaluation method, which uses an economic analysis technique. WLCCA allows comparison of investment alternatives having different cost streams. The analysis evaluates each alternative by estimating the costs and timing over a selected analysis period and converting these costs to economically comparable values considering time-value of money over predicted whole of life cycle. The analysis results can be presented in several different ways, but the most commonly used indicator in infrastructure/road asset management is the net present value of the investment option. The net present value of an investment alternative is equal to the sum of all costs and benefits associated with the alternatives discounted to today’s values [8].

Making a decision for selection of the rehabilitation method will be achieved by minimizing life cycle costs. Such a decision analysis is referred to as a whole of life cycle costing, cost-benefit or cost-benefit-risk analysis. Life cycle costs will assess the cost effectiveness of design decisions, quality of construction or inspection, maintenance and repair strategies [9]. The costs associated in a rehabilitation project may initially include:

- Initial cost
- Maintenance, monitoring and repair cost
- User cost
- Estimated cost of failure

As shown by Austroads [10] all of these costs are valued in resource cost terms (i.e. Market prices + subsidies - taxes). If monitoring, repair and extra user costs are considered as the maintenance cost then the cash flow for any rehabilitation method can be shown as in Figure 2.

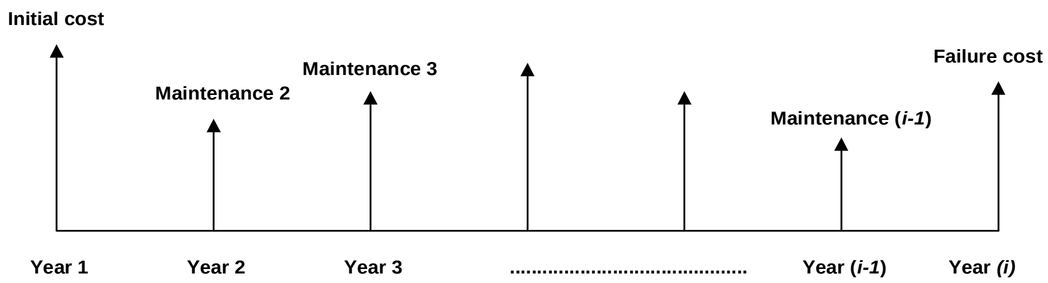

Figure 2: Cash flow for the rehabilitation of bridge

In order to be able to add and compare cash flows, these costs should be made time equivalent. The present value analysis may be considered together with the Internal Rate of Return (IRR).

8.0 Conclusions

A decision support framework was developed for selection of remedial action for reinforced concrete structures susceptible to degradation through exposure to aggressive environments such as marine conditions, extreme arid conditions and chemically active soils. The framework accounts for uncertainties associated with innovative technologies using a probabilistic concept, permitting the engineer to quantify and accept the level of reliability associated with the design. Guidelines may be developed for design of more sustainable civil infrastructure for aggressive environments based on the outcomes of the research in rehabilitation of the deteriorated structures. The major components of the framework have been identified as, case studies of deteriorating structures, evaluation of residual capacity using a probabilistic methodology, and conducting a life cycle cost analysis for each of the rehabilitation/treatment options.

Availability of innovative materials and new technologies for structural rehabilitation has opened up opportunities for more efficient structural rehabilitation. The advantages of using innovative materials and new technologies may be captured using the framework thus facilitating comparison of the different options available for rehabilitation. Probabilistic life cycle costing together with risk ranking offers significant improvements to the methodology of selecting the most suitable rehabilitation strategy. This approach is superior to the deterministic approach used in traditional bridge management systems.

9.0 Acknowledgements

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